

# Properties of Baryon Anti-decuplet

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We study the group structure of baryon anti-decuplet containing the  $\Theta^+$ . We derive the SU(3) mass relations among the pentaquark baryons in the anti-decuplet, when there is either no mixing or ideal mixing with the pentaquark octet, as advocated by Jaffe and Wilczek. This constitutes the Gell-Mann–Okubo mass formula for the pentaquark baryons. We also derive SU(3) symmetric Lagrangian for the interactions of the baryons in the anti-decuplet with the meson octet and the baryon octet. Our analysis for the decay widths of the anti-decuplet states suggests that the  $N(1710)$  is ruled out as a pure anti-decuplet state, but it may have anti-decuplet component in its wavefunction if the multiplet is mixed with the pentaquark octet.

PACS numbers: 11.30.-j, 12.40.Yx, 14.20.-c, 14.80.-J

The recent discovery of the  $\Theta^+$  baryon by LEPS Collaboration at SPring-8 [1], which has been confirmed by several groups [2], initiated a lot of theoretical works in the field of exotic hadrons. Experimentally, the  $\Theta^+$  is observed to have a mass of 1540 MeV and a decay width of  $< 25$  MeV. Because of its positive strangeness, the  $\Theta^+$  baryon is exotic since its minimal quark content should be  $uudd\bar{s}$ . Other states that have positive strangeness but different charges are not observed, which suggests that the  $\Theta^+$  is an isosinglet. The existence of such an exotic state with narrow width was first predicted by Diakonov *et al.* [3] in the chiral soliton model, where the  $\Theta^+$  is a member of the baryon anti-decuplet. Although it should be confirmed by other experiments, the recently discovered  $\Xi_{3/2}^-$  baryon [4] strongly supports the anti-decuplet nature of pentaquark baryons. The discussion on the existence of a baryon anti-decuplet has a longer history going back to the early 1970's [5], and in the Skyrme model [6]. Pentaquark states with a heavy antiquark ( $uudd\bar{c}$ ,  $uudd\bar{b}$ ) were also predicted in the Skyrme model. Here an important issue is whether such nonstrange heavy pentaquark states are stable against strong decays [7, 8, 9, 10, 11]. Subsequent theoretical investigations on the  $\Theta^+$  include approaches based on the constituent quark model [12, 13, 14], Skyrme model [15, 16, 17, 18, 19], QCD sum rules [20, 21], lattice QCD [22], chiral potential model [23], large  $N_c$  QCD [24], and Group theory approach [25]. The production of the  $\Theta^+$  was also discussed in relativistic nuclear collisions [26], where the number of the anti- $\Theta^+(1540)$  produced are expected to be similar to that of the  $\Theta^+(1540)$ .

Several pressing issues that should be clarified are whether the  $\Theta^+$  has positive or negative parity, and whether the Roper  $N(1710)$  is included in the baryon anti-decuplet with the  $\Theta^+$ . As for the spin-parity of the  $\Theta^+$ , several works claim that  $J^P = \frac{1}{2}^-$  is more natural [13, 21, 22], which, however, is in contrast to the prediction of the soliton models, where the relative orbital angular momentum plays an important role

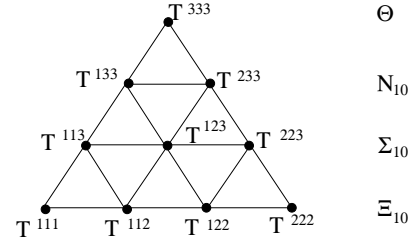


FIG. 1: A baryon anti-decuplet.

[9, 11]. The  $J^P = \frac{1}{2}^+$  assignment is also consistent with the recent study of the quark model [27], which predicts the lowest mass pentaquark state to be in the  $P$  wave state. The elementary production processes of the  $\Theta^+$  have been studied to address this question [28]. As for the structure of the anti-decuplet states, Jaffe and Wilczek proposed that the pentaquark is a diquark-diquark-antiquark state which is ideally mixed with the corresponding pentaquark in the octet [11]. In this approach, the  $N(1710)$  is classified as a member of the pentaquark states as in the chiral soliton model of Ref. [3], but the mass spectrum is totally different, as the mixing introduces the  $N(1440)$  as the lowest state among the pentaquark states. However, it is also claimed that such interpretation is doubted as the Roper resonances fall into the (excited) **56**-plets of SU(6) [29].

In this paper, we study the SU(3) flavor structure of the baryon anti-decuplet. We derive the SU(3) mass relations among the baryons in the anti-decuplet when there is either no mixing or ideal mixing with the pentaquark octet, where the later mixing scenario was advocated by Jaffe and Wilczek [11]. This constitutes the Gell-Mann–Okubo mass formula for the pentaquark baryons. We also derive the SU(3) symmetric interactions of the anti-decuplet with the baryon octet and pseudoscalar meson octet.

As shown in Fig. 1, we start by introducing the irreducible tensor notation  $T^{jkl}$  to represent the baryons in the anti-decuplet, which are denoted as the (0,3) repre-

	$Y$	$I_3$	$Q$	Particle
$T^{111}$	-1	$-\frac{3}{2}$	-2	$\sqrt{6}\Xi_{10}^{--}$
$T^{112}$	-1	$-\frac{1}{2}$	-1	$-\sqrt{2}\Xi_{10}^-$
$T^{113}$	0	-1	-1	$\sqrt{2}\Sigma_{10}^-$
$T^{122}$	-1	$\frac{1}{2}$	0	$\sqrt{2}\Xi_{10}^0$
$T^{123}$	0	0	0	$-\Sigma_{10}^0$
$T^{133}$	1	$-\frac{1}{2}$	0	$\sqrt{2}N_{10}^0$
$T^{222}$	-1	$\frac{3}{2}$	1	$-\sqrt{6}\Xi_{10}^+$
$T^{223}$	0	1	1	$-\sqrt{2}\Sigma_{10}^+$
$T^{233}$	1	$\frac{1}{2}$	1	$-\sqrt{2}N_{10}^+$
$T^{333}$	2	0	1	$\sqrt{6}\Theta^+$

TABLE I: Hypercharge, third component of isospin, charge, and physical state with proper normalization of the baryon anti-decuplet members. The phases are chosen to be consistent with Ref. [31].

sensation in the usual  $(p, q)$  notation [30]. Note that the baryon decuplet is in the  $(3, 0)$  and represented by  $T_{jkl}$ . Since  $T^{jkl}$  is an eigenstate of the hypercharge  $Y$  and the third component of the isospin  $I_3$ , one can directly match it with the physical baryon states. (See Table I.)

With these informations, we study baryon masses using SU(3) flavor symmetry. The well-known Gell-Mann–Okubo mass formula reads

$$M = M_0 + \alpha Y + \beta D_3^2, \quad (1)$$

where  $M_0$  is a common mass of a given multiplet and  $D_3^2 = I(I+1) - Y^2/4 - C/6$ , with  $C = 2(p+q) + \frac{2}{3}(p^2 + pq + q^2)$  for the  $(p, q)$  representation.  $\alpha$  and  $\beta$  are mass constants that are in principle different for different multiplets. Using these constants, one can write down the masses of all the baryon within a multiplet. Moreover, using these mass formulas, one can derive the well-known Gell-Mann–Okubo mass relation, the decuplet equal spacing rule, and the hyperfine splitting rule,

$$3M_\Lambda + M_\Sigma = 2(M_N + M_\Xi), \quad (2)$$

$$M_\Omega - M_{\Xi^*} = M_{\Xi^*} - M_{\Sigma^*} = M_{\Sigma^*} - M_\Delta, \quad (3)$$

$$M_{\Sigma^*} - M_\Sigma + \frac{3}{2}(M_\Sigma - M_\Lambda) = M_\Delta - M_N. \quad (4)$$

The last relation follows only if we assume  $\alpha_8 = \alpha_{10}$  and  $\beta_8 = \beta_{10}$ , where the subscripts 8, 10 represent the octet and decuplet representation respectively.

Using Eq. (1), the mass formulas for the baryon anti-decuplet can also be written down as follows,

$$\begin{aligned} M_\Theta &= M_{\overline{10}} + 2(\alpha_{\overline{10}} - \frac{3}{2}\beta_{\overline{10}}), \\ M_{N_{10}} &= M_{\overline{10}} + (\alpha_{\overline{10}} - \frac{3}{2}\beta_{\overline{10}}), \\ M_{\Sigma_{10}} &= M_{\overline{10}}, \\ M_{\Xi_{10}} &= M_{\overline{10}} - (\alpha_{\overline{10}} - \frac{3}{2}\beta_{\overline{10}}). \end{aligned} \quad (5)$$

We now discuss the anti-decuplet mass spectrum.

**Pure anti-decuplet:** Eq. (5) shows that the equal spacing rule holds also for the baryon anti-decuplet,

$$M_{\Xi_{10}} - M_{\Sigma_{10}} = M_{\Sigma_{10}} - M_{N_{10}} = M_{N_{10}} - M_\Theta, \quad (6)$$

which was already used in Ref. [3]. This suggests that if any two of the masses in the anti-decuplet are known, the other masses can be predicted by the mass relation. Using  $M_\Theta = 1540$  MeV and identifying the recent measurement of  $M_{\Xi_{3/2}} = 1862$  MeV by the NA49 experiment [4] as  $M_{\Xi_{10}}$ , we have

$$\begin{aligned} M_\Theta &= \underline{1540} \text{ MeV}, \quad M_{N_{10}} = 1647 \text{ MeV}, \\ M_{\Sigma_{10}} &= 1755 \text{ MeV}, \quad M_{\Xi_{10}} = \underline{1862} \text{ MeV}, \end{aligned} \quad (7)$$

where the masses used as input are underlined.

It should be noted that for the anti-decuplet, there are in fact only two independent parameters;  $M_{\overline{10}}$  and  $\delta m_{\overline{10}} = (\alpha_{\overline{10}} - \frac{3}{2}\beta_{\overline{10}})$ . This is also true for the decuplet;  $M_{10}$  and  $\delta m_{10} = (\alpha_{10} + \frac{3}{2}\beta_{10})$ . However, the mass parameters are quite different for the anti-decuplet  $\delta m_{\overline{10}} \sim -107$  MeV, and the decuplet  $\delta m_{10} \sim -150$  MeV. Moreover, if we assume  $\alpha_{\overline{10}} = \alpha_{10} = \alpha_8$  and  $\beta_{\overline{10}} = \beta_{10} = \beta_8$ , we would get an unrealistically large mass splitting  $\delta m_{\overline{10}} \sim -240$  MeV. The problem comes from using the parameters obtained from baryons with valence strange quarks only in the mass splitting for pentaquark baryon, where the anti-strange quark is also important in giving their mass splitting. That is why Jaffe and Wilczek introduced a phenomenological mass formula for the pentaquark states where the important mass splitting comes from not only terms proportional to the number of strange quarks  $n_s$  but also from terms proportional to  $n_{\bar{s}}$  [11],

$$\delta M = \gamma(n_s + n_{\bar{s}}), \quad (8)$$

which, however, does not change the mass relations (2)–(4).

**Ideal mixing with pentaquark octet:** Let us consider the mixing of the anti-decuplet with the pentaquark octet [11]. Using Eq. (1), we can write the masses of the pentaquark octet as

$$\begin{aligned} M_{N_8} &= M'_8 + \alpha'_8 - \frac{1}{2}\beta'_8, \\ M_{\Sigma_8} &= M'_8 + \beta'_8, \\ M_{\Xi_8} &= M'_8 - \alpha'_8 - \frac{1}{2}\beta'_8, \\ M_{\Lambda_8} &= M'_8 - \beta'_8. \end{aligned} \quad (9)$$

As in the model of Jaffe and Wilczek [11], we assume that the pentaquark octet and anti-decuplet are ideally mixed so that the  $s\bar{s}$  component is isolated,

$$N_{10} = \sqrt{\frac{1}{3}}N_q + \sqrt{\frac{2}{3}}N_s, \quad N_8 = \sqrt{\frac{2}{3}}N_q - \sqrt{\frac{1}{3}}N_s,$$

$$\Sigma_{10} = \sqrt{\frac{2}{3}}\Sigma_q + \sqrt{\frac{1}{3}}\Sigma_s, \quad \Sigma_8 = \sqrt{\frac{1}{3}}\Sigma_q - \sqrt{\frac{2}{3}}\Sigma_s, \quad (10)$$

where the subscript  $q$  ( $s$ ) means that the pentaquark has only light (strange) antiquark. Based on the above mixing formula, one can show that the original mass term in the Hamiltonian, if it has mixing between octet and anti-decuplet ( $c_1$  and  $c_2$  terms), is diagonalized as

$$\begin{aligned} H_m &= M_{N_{10}}N_{10}^2 + M_{N_8}N_8^2 + c_1N_{10}N_8 \\ &\quad + M_{\Sigma_{10}}\Sigma_{10}^2 + M_{\Sigma_8}\Sigma_8^2 + c_2\Sigma_{10}\Sigma_8 \\ &= (2M_{N_8} - M_{N_{10}})N_q^2 + (2M_{N_{10}} - M_{N_8})N_s^2 \\ &\quad + (2M_{\Sigma_{10}} - M_{\Sigma_8})\Sigma_q^2 + (2M_{\Sigma_8} - M_{\Sigma_{10}})\Sigma_s^2. \end{aligned} \quad (11)$$

Then we have

$$\begin{aligned} M_{N_q} &= 2(M'_8 + \alpha'_8 - \frac{1}{2}\beta'_8) - (M_{\overline{10}} + \delta m_{\overline{10}}), \\ M_{\Theta} &= M_{\overline{10}} + 2\delta m_{\overline{10}}, \\ M_{\Lambda_8} &= M'_8 - \beta'_8, \\ M_{\Sigma_q} &= 2M_{\overline{10}} - (M'_8 + \beta'_8), \\ M_{N_s} &= 2(M_{\overline{10}} + \delta m_{\overline{10}}) - (M'_8 + \alpha'_8 - \frac{1}{2}\beta'_8), \\ M_{\Xi_{10}} &= M_{\overline{10}} - \delta m_{\overline{10}}, \\ M_{\Xi_8} &= M'_8 - \alpha'_8 - \frac{1}{2}\beta'_8, \\ M_{\Sigma_s} &= 2(M'_8 + \beta'_8) - M_{\overline{10}}. \end{aligned} \quad (12)$$

There are eight masses and five parameters, hence three SU(3) mass relations. These are the generalized Gell-Mann–Okubo mass formula and anti-decuplet equal spacing rule and read

$$M_{N_q} + 2M_{N_s} = 2M_{\Theta} + M_{\Xi_{10}}, \quad (13)$$

$$2M_{\Sigma_q} + M_{\Sigma_s} = M_{\Theta} + 2M_{\Xi_{10}}, \quad (14)$$

$$3M_{\Lambda_8} = M_{\Sigma_q} + M_{N_q} + 2M_{\Xi_8} - M_{\Xi_{10}}. \quad (15)$$

These are the model independent SU(3) mass relations that should be satisfied by any model calculations.

So far, only two masses are known. To go further, we need some assumptions. First of all we will assume  $M_{\Xi_8} = M_{\Xi_{10}}$ . Next, as in Ref. [11], we assume  $M_{N_q} = 1440$  MeV, namely identify it with the Roper. Then we get  $M_{N_s} = 1751$  MeV, which is close to the  $N(1710)$ . If we further assume  $M_{\Lambda_8} = M_{\Sigma_q}$  [11], we obtain  $M_{\Lambda_8} = 1651$  MeV and  $M_{\Sigma_s} = 1962$  MeV. This is an improved mass spectrum based on the assumptions of Ref. [11].

Alternatively, we may turn on the phenomenological mass term in eq. (8) and assume that  $\alpha$ ,  $\beta$ , and  $\gamma$  are the same for all the multiplet. Then using  $M_N$ ,  $M_{\Sigma}$ ,  $M_{\Lambda}$ ,  $M_{\Theta}$ , and  $M_{\Xi_{10}}$  to fit these parameters, we obtain,

$$M_{N_q} = 1584 \text{ MeV}, \quad M_{\Theta} = \underline{1540} \text{ MeV},$$

$$\begin{aligned} M_{\Lambda_8} &= 1647 \text{ MeV}, \quad M_{\Sigma_q} = 1495 \text{ MeV}, \\ M_{N_s} &= 1679 \text{ MeV}, \quad M_{\Xi_{10}} = M_{\Xi_8} = \underline{1862} \text{ MeV}, \\ M_{\Sigma_s} &= 2274 \text{ MeV}, \end{aligned} \quad (16)$$

where the input masses are underlined. This is very different from the previous results and shows the sensitivity of the pentaquark mass spectrum on the assumptions made.

We now consider the SU(3) symmetric interaction of the anti-decuplet ( $\overline{D}$ ) with the baryon octet ( $B$ ) and the pseudoscalar meson octet ( $P$ ). The SU(3) symmetric interaction can be written as

$$\mathcal{L}_{\overline{D}PB} = -ig\overline{T}^{jkl}\gamma_5 P_m^j B_n^k \epsilon^{lmn} + \text{h.c.}, \quad (17)$$

where  $P_m^j$  is the pseudoscalar meson octet and  $B_n^k$  the baryon octet of which the expressions can be found, e.g, in Refs. [30, 32, 33]. Here we have used pseudoscalar coupling for the interaction, which can be readily replaced by pseudovector coupling by imposing chiral symmetry in the anti-decuplet sector. The universal coupling constant  $g$  can be determined from the  $\Theta^+$  decay width as  $g^2 = \Gamma_{\Theta}/(6.19 \text{ MeV})$ , which gives  $g \approx 0.9$  if  $\Gamma_{\Theta} = 5$  MeV [34]. But we notice the possibility that  $\Gamma_{\Theta}$  is much smaller [34]. In Table II, we give the full  $\overline{D}PB$  coupling constants, some of which were derived in Ref. [27]. We also note that the  $\Theta^+ K^0 p$  and  $\Theta^+ K^+ n$  interactions have different phase, which differs from Ref. [3], where the two couplings have the same phase.

The next step is to find the interactions of anti-decuplet with other multiplets. One can obtain the anti-decuplet interaction with the meson octet as

$$\mathcal{L}_{\overline{D}DP} = g'\overline{T}^{jkl}P_m^j T^{mkl}, \quad (18)$$

where we have dropped the Lorentz structure of the interaction. However, the interaction of  $\overline{D}PD$ , where  $D$  represents the baryon decuplet, is not allowed by SU(3) flavor symmetry. This is because  $\mathbf{8} \otimes \mathbf{10} = \mathbf{35} \oplus \mathbf{27} \oplus \mathbf{10} \oplus \mathbf{8}$ . So it cannot form an  $\overline{\mathbf{10}}$  and the  $\overline{D}PD$  interaction cannot be SU(3) singlet. This gives a very strong constraint on the properties of the  $N_{10}$  ( $\Theta^+$ ), since it is now prohibited to couple with  $\Delta\pi$  ( $\Delta K$ ) channel.

As an application, we compute the decay widths of the pure anti-decuplet members. Using the SU(3) Lagrangian, the total decay widths of the  $N_{10}$ ,  $\Sigma_{10}$ , and  $\Xi_{10}$  are approximately  $4 \times \Gamma_{\Theta}$ ,  $7 \times \Gamma_{\Theta}$ , and  $10 \times \Gamma_{\Theta}$ , respectively, which are expected to have some corrections if the decay channels into vector meson plus baryons are opened. As mentioned before, the  $N_{10}$  cannot decay into  $\Delta\pi$  because of SU(3) flavor symmetry. Furthermore,  $U$ -spin conservation does not allow its production from  $\gamma p$  reaction, while  $\gamma n$  reaction can generate the  $N_{10}$ . Since the  $N(1710)$  has large branching ratio of the decay into  $\Delta\pi$  and its coupling to  $\gamma p$  is larger than that to  $\gamma n$  [35], it cannot be a pure anti-decuplet state. Therefore, there is no candidate for the  $N_{10}$  among the known  $J^P = \frac{1}{2}^+$

$\Theta^+$		$N_{10}^+$		$N_{10}^0$		$\Sigma_{10}^+$	
$K^+n$	$\sqrt{6}$	$\pi^+n$	$-\sqrt{2}$	$\pi^0n$	1	$\pi^+\Lambda$	$-\sqrt{3}$
$K^0p$	$-\sqrt{6}$	$\pi^0p$	-1	$\pi^-p$	$-\sqrt{2}$	$\pi^+\Sigma^0$	1
		$\eta p$	$\sqrt{3}$	$\eta n$	$\sqrt{3}$	$\pi^0\Sigma^+$	-1
		$K^+\Lambda$	$-\sqrt{3}$	$K^+\Sigma^-$	$\sqrt{2}$	$\eta\Sigma^+$	$\sqrt{3}$
		$K^+\Sigma^0$	1	$K^0\Lambda$	$-\sqrt{3}$	$K^+\Xi^0$	$\sqrt{2}$
		$K^0\Sigma^+$	$\sqrt{2}$	$K^0\Sigma^0$	-1	$\bar{K}^0p$	$-\sqrt{2}$
$\Sigma_{10}^0$		$\Sigma_{10}^-$		$\Xi_{10}^+$		$\Xi_{10}^0$	
$\pi^+\Sigma^-$	-1	$\pi^0\Sigma^-$	1	$\pi^+\Xi^0$	$\sqrt{6}$	$\pi^+\Xi^-$	$\sqrt{2}$
$\pi^0\Lambda$	$-\sqrt{3}$	$\pi^-\Lambda$	$-\sqrt{3}$	$\bar{K}^0\Sigma^+$	$-\sqrt{6}$	$\pi^0\Xi^0$	-2
$\pi^-\Sigma^+$	1	$\pi^-\Sigma^0$	-1			$\bar{K}^0\Sigma^0$	2
$\eta\Sigma^0$	$\sqrt{3}$	$\eta\Sigma^-$	$\sqrt{3}$			$K^-\Sigma^+$	$\sqrt{2}$
$K^+\Xi^-$	-1	$K^0\Xi^-$	$-\sqrt{2}$				
$K^0\Xi^0$	-1	$K^-n$	$-\sqrt{2}$				
$\bar{K}^0n$	1						
$K^-p$	-1						
$\Xi_{10}^-$		$\Xi_{10}^{--}$					
$\pi^0\Xi^-$	-2	$\pi^-\Xi^-$	$-\sqrt{6}$				
$\pi^-\Xi^0$	$-\sqrt{2}$	$K^-\Sigma^-$	$-\sqrt{6}$				
$\bar{K}^0\Sigma^-$	$\sqrt{2}$						
$K^-\Sigma^0$	-2						

TABLE II: Couplings of the anti-decuplet with the baryon octet and pseudoscalar octet meson. Multiplying the universal coupling constant  $g$  is understood.

nucleon resonances [35]. The  $\Sigma(1770)$  with  $J^P = \frac{1}{2}^+$  may be a candidate for the  $\Sigma_{10}$ .

However, if we consider the mixing with octet, the analyses become more complex. The pentaquark octet can couple to meson octet and baryon octet through the familiar  $F$  and  $D$  type interactions, which introduces additional unknown coupling constants. It can also couple to meson octet and baryon decuplet. So the mixing debilitates the selection rules above. As far as the mass is concerned, if we use the assumption that gives (16), we found that the  $N_q$  is much higher than the  $N(1440)$ , but the  $N_s$  is close to the  $N(1710)$ . For the other states, we found that the  $\Lambda(1600)$  with  $\frac{1}{2}^+$  can be a candidate for the  $\Lambda_8$ . As possible candidates for  $\Sigma_q$  and  $\Sigma_s$ , we found  $\Sigma(1480)$  and  $\Sigma(2250)$  bumps in Particle Data Group [35] although their quantum numbers are not fixed yet.

Y.O. is grateful to the hospitality of Jefferson Lab., where this work was completed. This work was supported by Korea Research Foundation Grant (KRF-2002-015-CP0074).

*Note added.* After completion of this work, we were aware of a recent work of Diakonov and Petrov [36], which discussed the mixing angles and similar mass relations in pentaquark states.

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